High-Efficiency Low-Dross Combustion System For Aluminum Remelting Reverberatory Furnaces

Annual Technical Progress Report For The Period July 1, 2001 – June 30, 2002

By
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Work Performed Under Contract No. DE-FC07-00ID13903

For U. S. Department Of Energy
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By
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EXECUTIVE SUMMARY

This report presents the work performed by the Gas Technology Institute and subcontractors Eclipse Combustion, the University of Illinois at Chicago and Wabash Alloys, during the period from July 1, 2001 – June 30, 2002 under contract (No.: DE-FC07-00ID13903) with the U. S. Department of Energy.

GTI, and its commercial partners, have developed a high-efficiency low-dross combustion system that offers environmental and energy efficiency benefits at lower capital costs for the secondary aluminum industry users of reverberatory furnaces. The high-efficiency low-dross combustion system includes the flex-flame burner firing an air or oxygen-enriched natural gas flame, a non-contact optical flame sensor, and a combustion control system. The flex-flame burner, developed and tested by GTI, provides an innovative firing process in which the flame shape and velocity can be controlled. The burner produces a flame that keeps oxygen away from the bath surface by including an O_2-enriched fuel-rich zone on the bottom and an air-fired fuel-lean zone on the top. Flame shape and velocity can be changed at constant firing rate or held constant over a range of firing conditions. A non-intrusive optical sensor is used to monitor and control the flame at all times. Information from the optical sensor(s) and thermocouples is used to control the flow of natural gas, air, and oxygen to the burner as needed to maintain desired flame characteristics. This type of control is particularly important to keep oxygen away from the melt surface and thus reduce dross formation.

This retrofit technology decreases fuel usage, increases furnace production rate, lowers gaseous emissions, and dramatically reduces dross formation. The highest priority research need listed under Recycled Materials is to turn aluminum process waste into usable materials which this technology accomplishes directly by decreasing dross formation and therefore increasing aluminum yield from a gas-fired reverberatory furnace. Emissions of NO_x will be reduced to approximately 0.3 lb/ton of aluminum, in compliance with air emission regulations.

The objective of this project is to develop the high-efficiency low-dross combustion system and to demonstrate this advanced combustion system on an industrial reverberatory furnace. At the completion of this project, with the aid of the Industrial Adoption Plan to be prepared and updated throughout the project, the technology will be ready for commercial application.

The project is organized in a single Phase with multiple Tasks and will be conducted over 36 months. Milestones have been defined for each project year, and go/no-go decisions have been placed at the end of years 1 and 2 to enable project sponsors to make objective judgments regarding continued project work based on achievement of specified objectives. Work during the three years of this project includes:

Year 1.
Test the flexible burner concept on the laboratory scale. Install and test on GTI's 0.5 MM Btu/h furnace. Test and measure emissions and heat release characteristics over a wide range of operating parameters (aluminum melting process needs). Measure gas compositions under the flame using conventional sampling probes. Design non-contact sensor(s) for gas composition and flame shape measurement inside the furnace.

Year 2.
Test 3 MM Btu/h system on GTI's modular test furnace for emissions and process performance. Develop, install and calibrate non-contact flame shape and gas sensor(s) for controlling the fuel-rich, O_2-free zone over the bath. Test integrated sensor, burner, and automatic process control system on the 3 MM Btu/h furnace. Identify host reverberatory furnace for demonstration testing in Year 3.

Year 3.
Field test system on a host reverberatory furnace and finalize the commercialization plan. Field testing will begin by first testing the flex-flame burner part of the combustion system as a typical furnace burner. Then the non-contact flame sensor(s) will be installed and calibrated. The sensor(s) and furnace thermocouples will be connected to the control system and proper sensing and control output will be verified. Finally, a field test will be conducted in which the complete combustion system is operating, with the control system using sensor input to control the flex-flame burner(s).

This report presents a summary of work conducted during the second year of the project. Results of work conducted during the first project year are presented in the Year 1 Annual Report.

During the fifth quarter, significant work was conducted to test the needed new optical sensor for richer and leaner flame zones and to develop the flex-flame burner with rich and lean flame zones. A laboratory-scale flex-flame burner was fabricated, and testing was conducted. Work included testing the complete optical sensor with the laboratory-scale nozzle-mixed turbulent flame along with testing and modification of the first laboratory version of the flex-flame burner. Testing has demonstrated the ability to control flame shape and characteristics, to create flame zones that are fuel richer and leaner, to create a flame that is significantly richer on one side and leaner on the other, and to measure air to fuel ratios in selected flame regions.

During the sixth quarter, various flames generated with the flex flame burner system were studied. This work included spectroscopic examination of flame structure and further analysis, as well as investigation of the flue gas composition using conventional combustion gas analyzers. A large spectroscopic characteristics database was generated during the experiments. The major accomplishment of this quarter was establishing the necessary burner configuration, oxidizer and fuel flow conditions and ultimately flame parameters, in order to create the hybrid flame. The developed hybrid flame has significantly lower oxygen concentration distribution in the portion of the flame facing the aluminum melt layer relative to the oxygen concentration in conventional nozzle mix flames. This technique is expected to help significantly reduce aluminum melt oxidation and reduce dross formation. At the same time, the developed hybrid flame does not emit carbon monoxide pollution and remains efficient. Now the developed technology of the hybrid flame burner prototype can be directly utilized in the development of the medium sized industrial 0.5 – 1 MMBtu/h hybrid flame burner to be tested on a fully instrumented GTI test furnace.

During the seventh quarter, the laboratory equipment was moved into the new combustion laboratory for optical studies. This new location allows experiments to be conducted without the contamination of stray light. Experimental work with air and oxy-enriched flames were continued. Initial plans for the nozzle-mixed pilot-scale burner were

During the eighth quarter, flame investigation experiments were performed for three different flame configurations: oxygen enriched flame, flame with portion of the fuel admixed to the all four air nozzles, and a flame with a portion of the fuel admixed to the two nozzles on the right side of the burner. The evolution of two important radical species, OH and CH, was observed and quantified at one-inch increment along the flame using the laboratory version of the Rich/Lean sensor.. Furthermore, emissions (O_2, CO, CO_2, and NOx) from the flue gas were measured at the right and left side of the burner with a Horiba portable gas analyzer. Conclusions were reached regarding desired degrees of mixing. Work was begun on designing the pilot-scale flex-flame burner. This burner will be fabricated at the start of the next quarter and will be tested independently and coupled with the fuel rich-lean sensor.

ANNUAL PROGRESS REPORT

Project Title	High-Efficiency Low-Dross Combustion System for Aluminum Remelt Reverberatory Furnaces
Covering Period	July 1, 2001 through June 30, 2002
Date of Report	July 31, 2002
Recipient	Gas Technology Institute 1700 S. Mt. Prospect Rd. Des Plaines, IL 60018
Award Number	DE-FC07-00ID13903
Subcontractors	University of Illinois at Chicago Eclipse, Inc.
Other Partners	Southern California Gas Co. – project sponsor GTI Sustaining Membership Program (SMP) – project sponsor Wabash Alloys – industrial host site partner

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Project Objective

The objective of this project is to develop and demonstrate the high-efficiency low-dross combustion system for reverberatory furnaces used for aluminum remelting.

Reverberatory furnaces typically have a low efficiency because the liquid aluminum reflects a large fraction of the available heat. The furnace refractory is heated, and radiation from the hot refractory heats the melt in the bath. Although a number of exhaust gas heat recovery techniques have been developed and employed, furnace efficiencies remain low, often at values around 25 percent. The objective of this project is to use an O_2-enriched combustion process with burners capable of flame shaped adjustment to provide significantly greater energy efficiency than present reverberatory furnaces combustion systems.

Economic and environmental analyses have found that the greatest cost savings from an improved combustion system are realized from the reduction in dross. Dross is largely aluminum oxide formed by reaction of oxygen with the molten aluminum. The high-efficiency low-dross combustion system decreases dross by an estimated 60 percent by blanketing the surface of the melt with an oxygen-free zone produced by a fuel-rich flame. This combustion system creates a flame that is oxygen-free and fuel rich on the bottom close to the bath surface and fuel-lean for CO and VOC burn-out on top. Dross is also reduced by controlling the temperature of the bath surface. Hot spots are the second major component in dross formation. This advanced combustion system eliminates the two leading causes of dross formation, oxygen contact with the molten aluminum and local hot spots on the surface of the bath.

Energy cost is less than 20 percent of the cost of secondary aluminum melting. Therefore, saving 40% of the natural gas required for heating and purchasing needed oxygen provides only a small economic benefit to the reverberatory furnace operator. Decreasing the dross which also increases the aluminum yield per pound, decreases dross handling and processing, and decreases the amount of salt cake formed and subsequently sent for disposal. A key objective of this project is to develop a combustion system that improves process energy efficiency and economics by greatly reducing the amount of dross formed.

This project is divided into three 12-month long Phases, each consisting of five specific Tasks. The work involved in each Phase and Task is detailed in Section 4.3. Specific objectives have been defined for each project year to provide a means of assessing project progress and making go/no-go decisions regarding project continuation in subsequent years. The specific objectives for the first project Phase, covering the first 12 months are,

- Demonstration of flame that is fuel-rich on the bottom and fuel-lean on the top,
- Design and fabrication of a flex-flame burner system incorporating the axisymmetric fuel-rich and fuel-lean flame as well as O_2-enriched combustion and complete flexibility to control flame shape at constant firing rate or to maintain flame shape over a wide range of firing rates (over a turn-down ratio of at least 4:1).
- Verify combustion control with the flex-flame burner on a 0.5 MMBtu/h laboratory furnace and confirm sensor capability to monitor flame shape,
- Begin developing an Industrial Adoption Plan for this advanced combustion system by determined market size, companies operating reverberatory furnaces, and potential applications.

Specific objectives or milestones for all three project Phases are described below.

Background

The high-efficiency low-dross combustion system provides interactive and flexible control of the combustion process in aluminum remelting reverberatory furnaces. This advanced combustion system dramatically reduces dross formation while providing the flexibility to produce maximum heat transfer to the bath over high turn-down ratios through the full melting/degassing/tapping cycle.

The high-efficiency low-dross combustion system integrates two components with an automatic real-time combustion control system. The components of the combustion system are an oxygen-enriched flex-flame burner that reduces fuel use and emissions while dramatically reducing dross and a non-intrusive optical sensor such as a chemi-luminescent C_2^+ sensor. A schematic of the high-efficiency low-dross combustion system in operation is shown below.

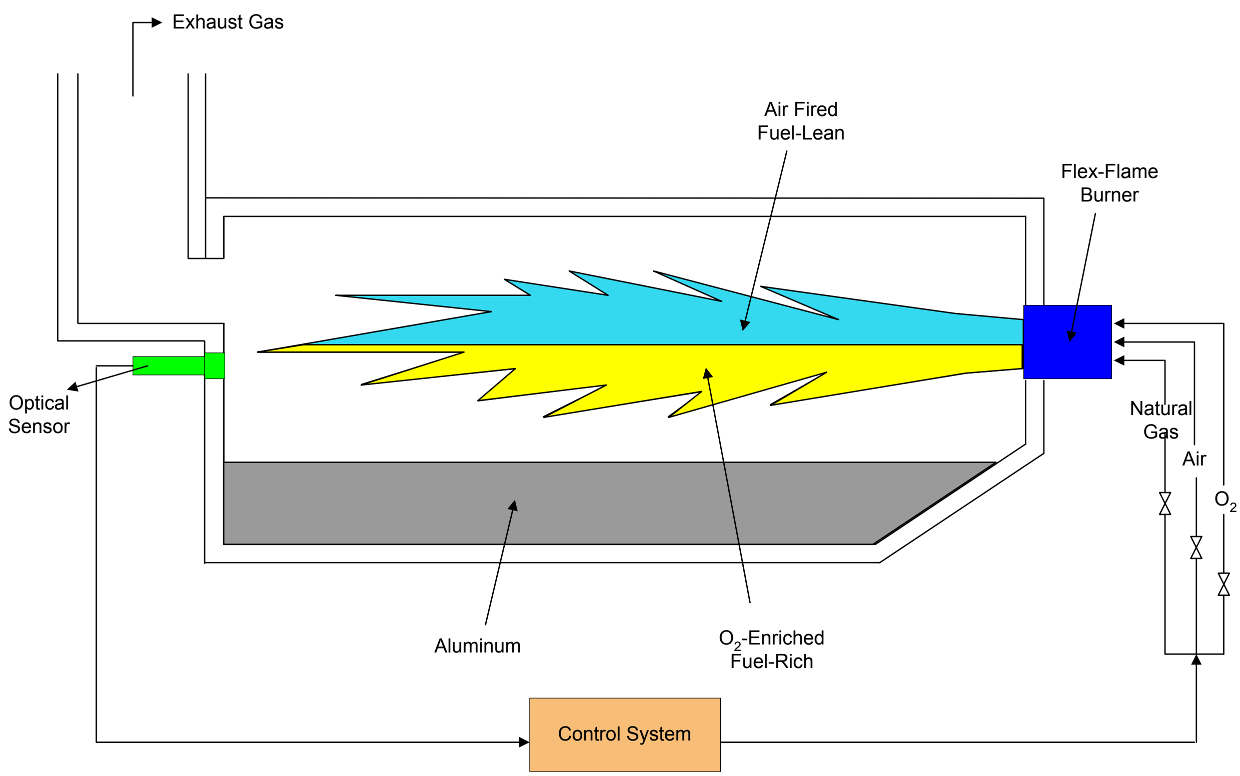


FIGURE 1**. THE HIGH-EFFICIENCY LOW-DROSS COMBUSTION SYSTEM IN OPERATION**

The high-efficiency low-dross combustion system uses an enriched-oxygen hybrid flame with a fuel-rich zone on the bottom and a fuel-lean zone on top. Firing is through a special flex-flame burner that produces this hybrid flame and can also be adjusted for flame shape. A non-contact optical sensor is used to observe the flame in real time and to provide input information to the combustion control system. This complete combustion system operates automatically to provide the highest possible efficiency while keeping dross formation to a minimum.

The Flex-Flame burner family – The simple, highly adjustable Flex-Flame family of burners includes features to provide a wide range of operating conditions. Capabilities of this advanced burner design include –

- Hybrid flame production with a fuel-rich zone (air-fired or O_2-enriched) on the bottom and an air-fired fuel-lean zone on top
- High turn-down ratio
- Automatic air to fuel and O_2-enriched air to fuel ratio adjustments
- Automatic flame shape adjustment at constant fire
- Automatic flame velocity control over wide turn-down ratio
- Automatic air or fuel staging adjustment between the fuel-rich and fuel-lean combustion zones
- Automatic mixing pattern control through velocity control

The Flex-Flame burner geometry is proprietary to GTI. Adjustments for these burners require no direct contact of hot moving parts. This robust design leads to low maintenance and long service life. A concept schematic drawing of the Flex-Flame burner is presented below.

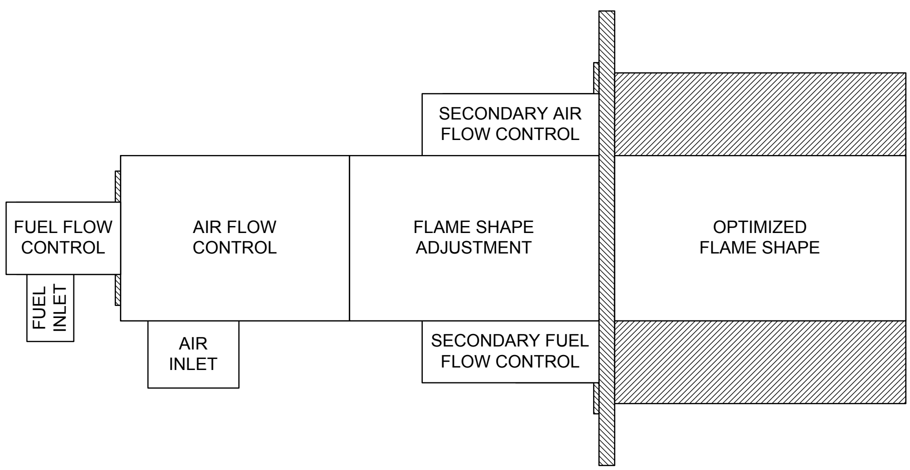


FIGURE 2. **FLEX-FLAME BURNER CONCEPT**

Real-time Flame Sensing and Control – A non-intrusive optical system is used to observe the flame and provide information for automatic, real-time, control of the combustion process. Measurements will likely be made of C_2^+ species using a chemi-luminescent sensor. Capabilities of the sensing and control system include –

- Measurement of the flame shape including length and width
- Measurement of mixing by observing luminosity of flame regions
- Detection of emissions in the flame including CO and NO_x
- Data processing and integral, feed-back control algorithms to provide combustion monitoring and control

- Rapid response to adjust the combustion process to furnace instabilities, fuel changes, firing rate (turn-down), and non-steady state process heating

Real-time flame sensing and control uses new, state-of-the-art optical measurement techniques to provide complete, real-time control of the combustion process. The system is flexible for application to specific applications.

Status

The work plan for years one and two focuses on laboratory testing and development. Included in this are the following tasks:

- Lab-scale flex flame burner design, fabrication, and testing
- Flame sensor design, fabrication, and installation
- Lab-scale testing of complete SOCS system

Organizational meetings with the parties involved in this project have led to the work effort displayed in Figure 3

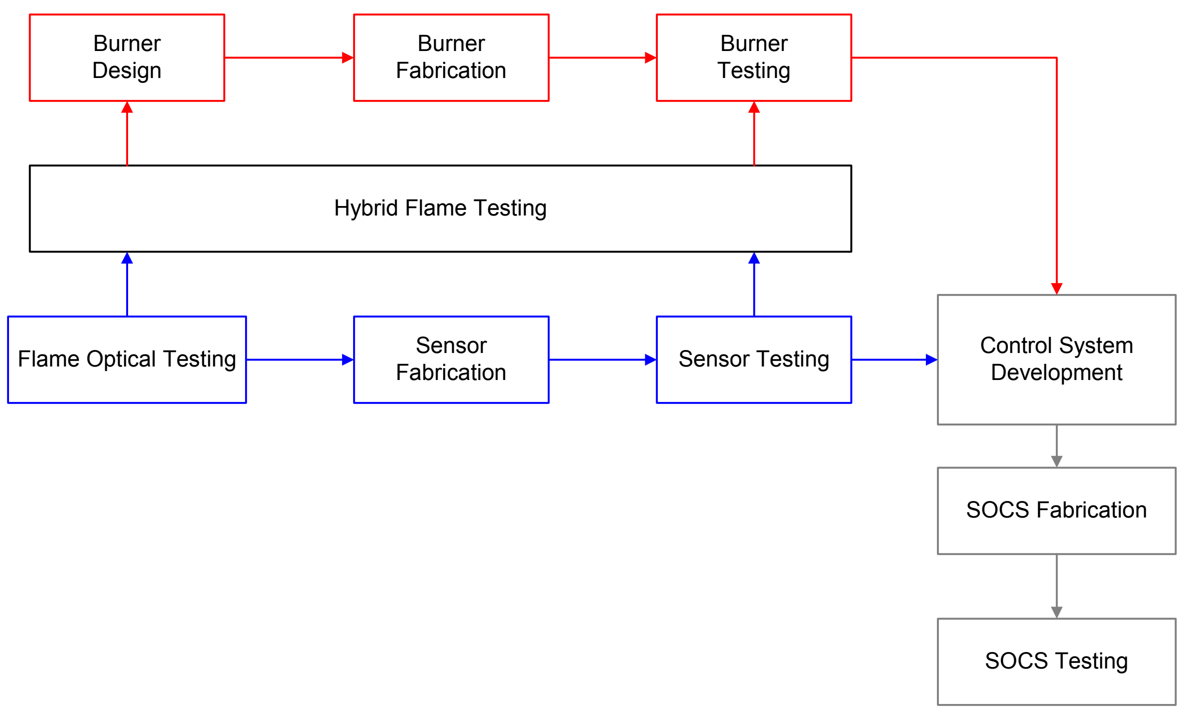


FIGURE 3. YEARS 1 AND 2 WORK EFFORT FLOWCHART.

Integral to the project success is the development and testing of the SOCS system in an industrial application. Despite year one focusing more on a laboratory scale, the project team members felt it important in the initial stages of the project to establish the operational conditions and requirements of an industrial application of the SOCS system. In order to understand and document these requirements, the GTI project participants visited Wabash

Alloys production facility in Wabash, IN. The facility produces aluminum alloys from recycled or scrap products. From this meeting important information such as the operational parameters of the existing furnace and current combustion system were collected. After this meeting, GTI developed a questionnaire for the purpose of gathering more information about the furnace.

An important issue that came from the meeting with Wabash is the chemical mechanism that is involved in the formation of the dross or the aluminum oxide on the surface of the aluminum melt. Performance history of the remelt furnace suggests that other parameters as well as the presence of oxygen in the furnace have a dramatic effect on the formation of dross. GTI, and subcontractor UIC, have conducted an extensive literature search into this problem to assist in establishing the operational parameters of the SOCS system to further lower dross production.

Studies of molten aluminum oxidation

Literature search results found dross formation is a complex phenomenon dependent on many factors. Oxidation increases strongly with increasing molten aluminum temperature. Higher partial pressures of oxygen, steam, and hydrogen lead to greater oxidation, while nitrogen and carbon dioxide decrease the oxidation reaction rate. Oxidation increases with accessibility of the molten aluminum surface. Therefore, covering the surface with a salt layer during melting and disturbing the surface as little as possible both lead to lower aluminum oxidation. Finally, different alloys experience different oxidation rates. Higher magnesium content alloys oxidize faster than lower magnesium alloys or pure aluminum.

An aluminum alloy containing magnesium was melted in the first quarter of this year in iron crucibles inside an electric furnace. During the heating period, the samples were exposed to atmospheres containing different ratios of oxygen and nitrogen. All samples underwent oxidation, and an oxide film was formed on the aluminum alloy surface. Testing also showed that oxidation increased with increasing oxygen partial pressure. Unfortunately, the tests were not accurate enough to determine the quantitative relationship between oxygen partial pressure and aluminum oxidation. Tests next quarter under more controlled test conditions will attempt to acquire this information.

FLAME SPECTROSCOPIC MEASUREMENTS

One-dimensional flat flames were generated using an adiabatic flat flame burner. Our choice of a flat flame for the initial experiments is based on the necessity to produce a well-controlled and measurable volume of flame with known parameters.

Spontaneous emission spectrums of the flame generated molecules and radicals (including CH, OH and C_2) were measured and recorded for the flames of several equivalence ratios (the stoichiometric air/fuel ratio over the actual air/fuel ratio). (Figure 4)

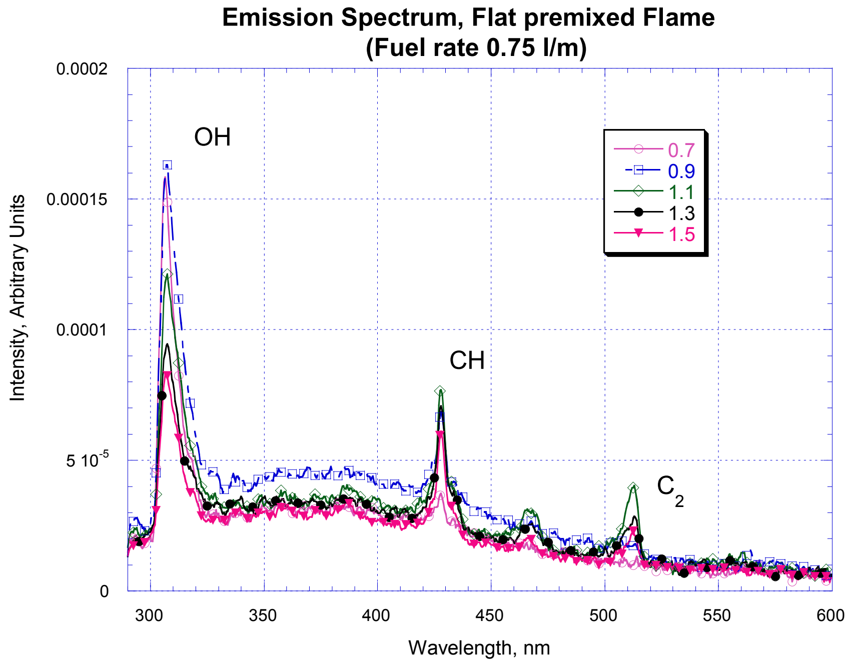


Figure 4. EMISSIONS SPECTRUM, FLAT PREMIXED FLAME
(Fuel Rate of 0.75l/min)

The flat flame experiments showed that the obtained spectral characteristics can be uniquely related to the equivalence ratio of the premixed flames and are independent of the firing rate (meaning total heat release and the size of the flame). This will enable development of a sensor capable of real time monitoring of rich/lean structure of flames and fuel/oxidizer mixing processes. In Figure 5 the ratio of the two highest peaks of the spectrums I_{OH}/I_{CH} are plotted versus the flame equivalence ratio.

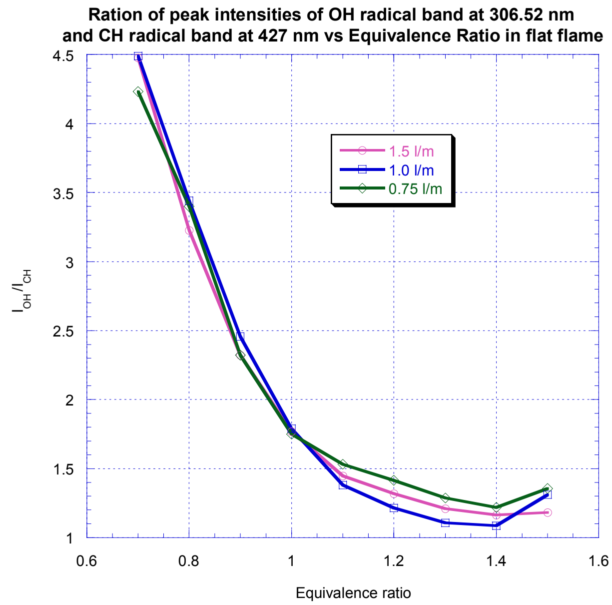


Figure 5. RATIO OF THE PEAK OH AND CH RADICALS' EMISSION INTENSITIES IN FLAT FLAMES

Flex Flame Experiments.

A laboratory-scale version of the flex-flame burner was designed, fabricated and installed at the GTI Combustion Laboratory. It can be fired at rates of 0.02 to 0.4 MMBtu/h. The burner was designed to allow adjustment of flame shape, flame length, and mixing patterns. This burner was tested along with the optical flame sensor also developed at GTI and coupled with the flex flame burner. Besides the burner and the sensor, the developed Flex Flame experimental set up included controls from MKS Inc and a PC based data acquisition system.

The schematic of this experimental setup and a photo of the laboratory equipment were presented in an earlier quarterly report. Experiments showed that the I_{OH}/I_{CH} ratio does not depend upon the firing rate, it depends on the flame configuration and the ratio of oxidizer and fuel supplied to the combustion zone.

Similar to the premixed turbulent jets, OH and CH emission intensities first increase until they reach their maximums in the upper half portion of the flames. The emission peaks of CH radicals are lower than the OH peaks in the spectrums at any location along the flame. The concentration of the CH radicals in the A/F=1.43 lean flame is low due to the fast carbon oxidation to CO and finally to CO_2 in the abundance of oxygen and oxidizing radicals (for example OH). I_{OH}/I_{CH} ratio values calculated for the spectrums obtained in the richer flames (for examples A/F=1.00) are lower than in I_{OH}/I_{CH} calculated for leaner flames. This is consistent with the premixed flame experiments results.

To acquire and process spectral images we used a combination of GTI developed software and “SpectraSence” software supplied by Roper Scientific Co. Figure 6 shows examples of the obtain spectrums.

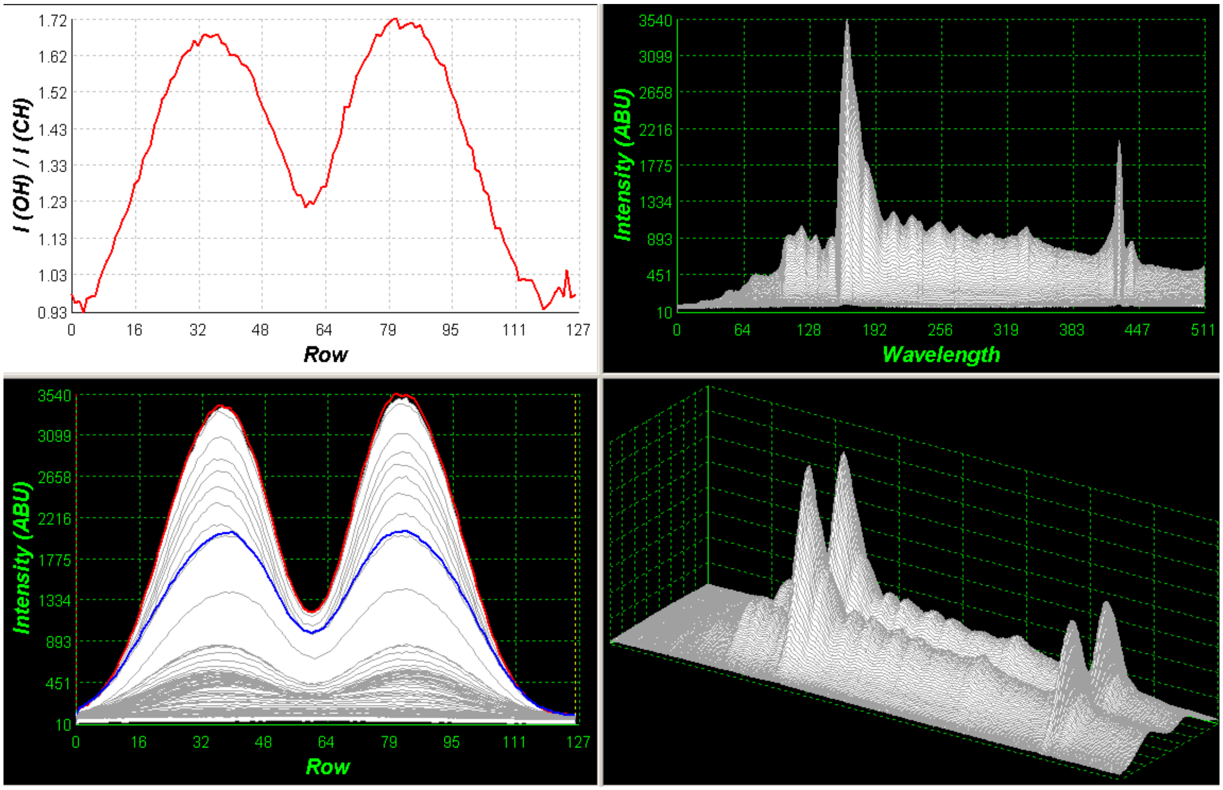


Figure 6. SPECTRUMS OF THE A/F =1.05 TURBULENT NOZZLE MIXED FLAME

Measurements were made of CH and OH radical concentrations along the length of the test flames. Figures 18 and 19 show CH and OH peaks and the CH/OH peaks at different flame heights for a richer flame with air/fuel ratio of 1.00. Figures 20 and 21 present the same information for a leaner flame with an air/fuel ratio of 1.05. For all tests, the burner firing rate was 30,000 Btu/h. The figures clearly show the differences in the radical ratios. This difference will be used in coming months to develop the industrial version of the sensor.

A series of tests was conducted to create a nozzle mixed flame that is more fuel rich on one side and more fuel lean on the other side. Results were positive. These detailed results were presented in an earlier quarterly report. Figure 7 summarizes the radical concentration ratios on the right and left side of the flame.

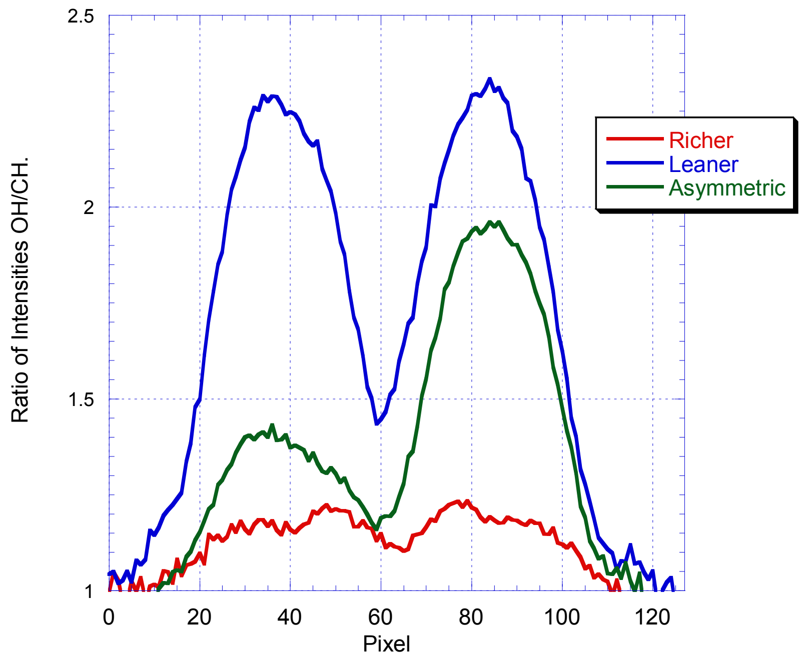


Figure 7. OH TO CH RATIOS SCANNING ACROSS THE FLAME FOR RICHER, LEANER, AND ASYMMETRIC FLAMES

The next project objective was to establish the necessary burner configuration, oxidizer and fuel flow conditions and ultimately flame parameters, in order to create a so-called hybrid flame. The concept of such a flame is shown in Figure 8. This flame has to have a smaller oxygen concentration in the portion of the flame facing the aluminum melt layer relative to the rest of the flame. This is expected to affect design considerations for the pilot scale hybrid flame burner to be tested on the GTI test furnace.

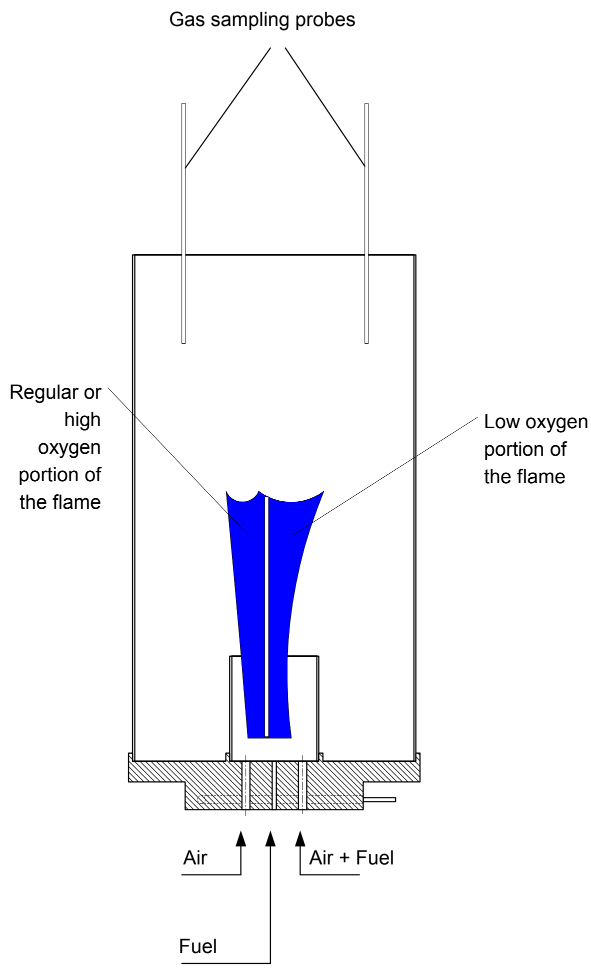


Figure 8. CONFIGURATION OF FLEX FLAME BURNER FOR HYBRID FLAME GENERATION

The experimental set up used to generate the hybrid flames is depicted in Figures 6 and 7, and described on page 17. Spectroscopic measurements of lean/rich flame patterns were supplemented with conventional flue gas analysis. A Quintax Combustion analyzer was utilized to measure flue compositions at two locations over the flame, as it shown in Figure 8.

Typically, nozzle mixed burners generate stable, low NO_x controllable flames. This type of burner has been widely used in various furnaces and other combustion apparatuses including aluminum remelt furnaces, glass-melting furnaces, etc.

Nozzle mix burners partially premix the oxidizer and fuel within the nozzle causing the flame to have some attributes of both premixed and non-premixed combustion. The relative proportions depend on the degree of mixing achieved at the nozzle. [Stephen R. Turns, “Introduction to combustion”.] Therefore, the location and combustion characteristics of the conventional nozzle mixed flame depend on how well the burner design is configured to produce necessary mixing at a necessary rate. Even though the combustion process can be controlled by controlling the mixing process, the ability to control mixing and chemical processes in the burner is limited.

Normally nozzle mixed burners are operated under 5-10 % excess air to ensure complete combustion and prevent carbon monoxide pollution. Such significant air excess results in the presence of a significant amount of oxygen in the flue gas. The major challenge in the development of the new low dross flex flame burner is to create combustion conditions where fuel is completely oxidized and oxygen left over in the flue gas is kept to the minimum possible concentration over the aluminum. Normally, combustion processes in nozzle mixed flames are controlled by the rate of mixing of the fuel and oxidizer. To create a lower oxygen flue gas environment in the right portion of the flame, small amounts of fuel were admixed to the right two air nozzles leaving the left nozzles ejecting pure air into the mixing nozzle. The admixing of a small amount of fuel into the right hand side oxidizer's nozzles resulted in a new flame structure on the right side of the flex flame burner. Detailed results of this testing were presented in an earlier quarterly report. During the initial stages of this project it was established that lean premixed flames emit nearly exclusively at 310 nm, which corresponds to the OH emission band. Therefore, the presence of new OH emission enhancement can be explained by the presence of a new premixed flame formation existing at approximately the same location with the conventional nozzle mixed flame structure. This fact can be explained by the creation of a new turbulent double flame structure. The new double flames demonstrates features of the conventional nozzle mix flame while evidently displaying properties of a lean premixed flame.

Premixed flames can exist only under certain thermal, physical and chemical conditions of the oxidizer-fuel mixture. This means that premixed flames can be sustained when enough energy is released into the oxidizer-fuel mixture and the ignition criteria are satisfied.

Flame stability and flammability limits of lean premixed flames can be influenced by the transfer of active radicals and heat from other zones of the nozzle mix flame structure.

Oxygen concentrations in the flue were measured at two locations at approximately 25 inch over the burner base (see Figure 8). The purpose of these measurements was to use conventional combustion gas analyses techniques to determine if a low oxygen flue gas zone can be created without affecting the burner efficiency and pollution emission characteristic. Experiments showed that the addition of a small amount of fuel to the right side air nozzles with the same reduction of fuel flow rate in the main fuel port resulted in a redistribution of "left over" oxygen concentration profile in the flue gas stream. Figure 9 shows that the concentration of oxygen in the right portion of the burner decreased while the oxygen concentration in left portion of the burner increased. Therefore, the results showed that the oxygen concentration distribution in the flue gas can be controlled via not only varying overall Air to Fuel Ratio, but also by controlling the structure and mode of the combustion process in the flex flame burner. The technique involving flame structure manipulation and control looks very useful for the development of a new generation of flex-flame burners.

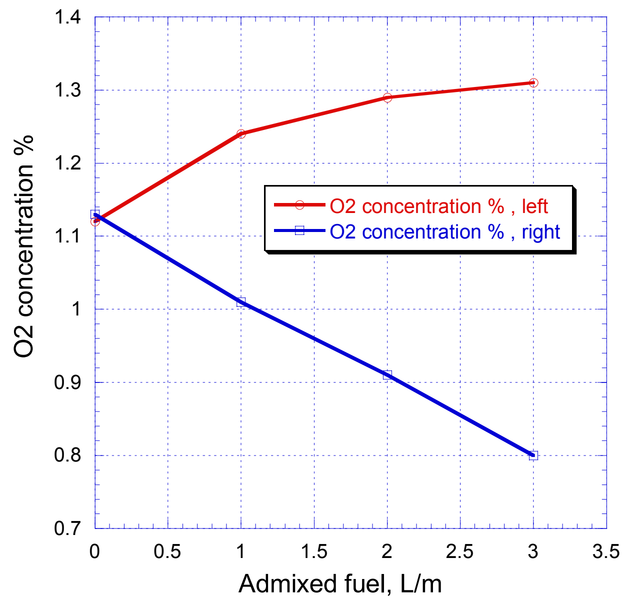


Figure 9. Oxygen concentration vs. amount of fuel admixed to the right side air nozzles distribution in regular (0 l/m admixing) and double flame configuration

Flex Flame Burner modeling work was carried out by UIC this year. Results of that work were presented in an Appendix to one of the quarterly reports.

In the third quarter of this year, the laboratory equipment was moved into a new GTI combustion laboratory for optical studies. This new location allows experiments to be conducted without the contamination of stray light. Below is a photograph of the new lab and the test equipment.

Figure 10 The new combustion laboratory for sensor development.
Room is isolated in order to avoid stray light contamination.

In addition to the existing equipment moved into the new laboratory, a new Horiba gas analyzer was installed and tested. This new gas analyzer is capable of giving more accurate measurements with a faster response time than the previous system. Data acquired using this new analyzer is shown in Figures 12 (a) & (b).

A photograph of a test flame in the new laboratory is shown in Figure 11. Here the two sides of the flame are very distinct. The blue color of the flame is characteristic of the lean flames used in the experiments here.

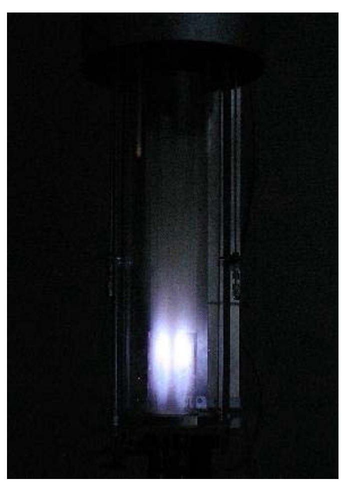


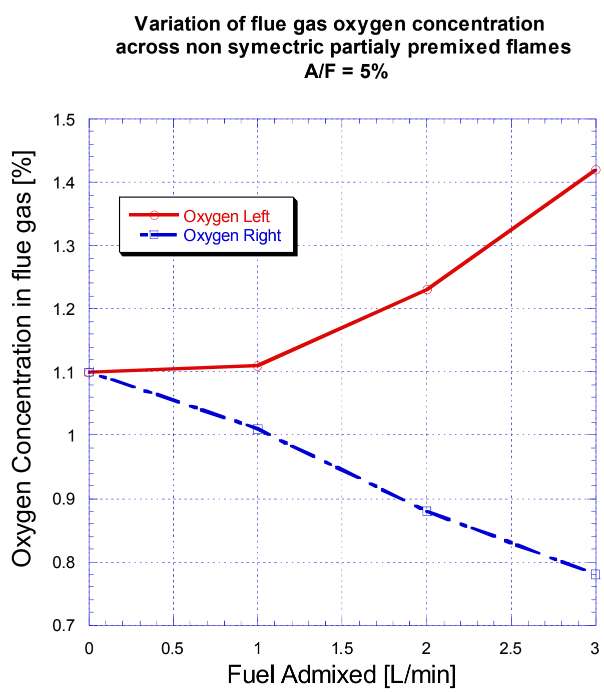
Figure 11. Flame photograph showing two distinct sides of the flame

The experiments conducted in the previous laboratory were repeated to ensure that the system remained consistent after the move. The experiments included those shown in the test matrix below.

0L/min admix 5% excess air	1L/min admix 5% excess air	2L/min admix 5% excess air	3L/min admix 5% excess air
0L/min admix 10% excess air	1L/min admix 10% excess air	2L/min admix 10% excess air	3L/min admix 10% excess air

Test matrix performed where air flow rate was varied between 5% and 10% excess air and the fuel admixing to one side of the flame ranged from 0 – 3 L/min. Total fuel is 10 L/min.

The spectroscopic measurements from these experiments show strong similarity to those obtained previously, leading to confidence that the tests were consistent with data previously acquired. Also, the oxygen concentrations within the flu gas were obtained, for the right and left side of the burner. These concentrations were shown to vary with changing admixing amounts, as in previous experiments. This data is shown below in Figure 12 (a) and (b). Figure 12 (a) shows the flu gas oxygen concentrations for the 5% excess air case, and Figure 12 (b) for the 10% excess air case.



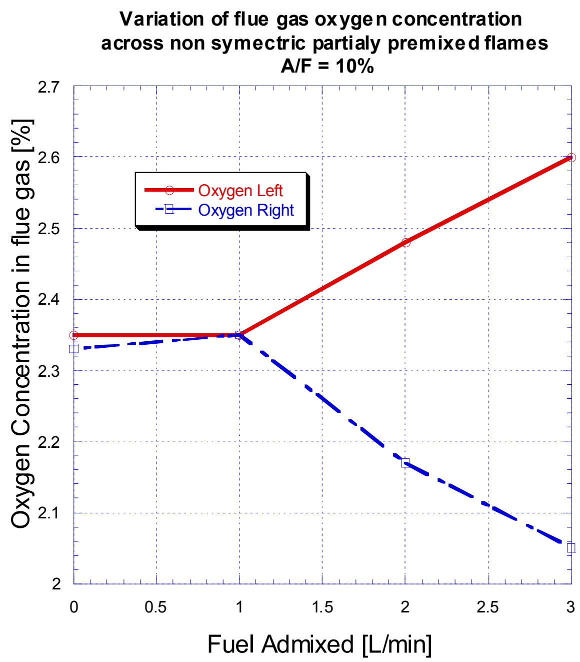


Figure 12: Oxygen concentrations in the flu gas with varying fuel admixing for test cases with (a) 5% and (b) 10% excess air.

Figures 12 (a) and (b) show that the oxidizing atmosphere of the flue gas can be controlled by admixing fuel to one side of the flame. For both 5% and 10% excess air, this effect becomes apparent when slightly more than 1 L/min of fuel, out of the 15 L/min of fuel in the central jet, is admixed for. For both cases, admixing 3 L/min of fuel reduced the concentration of oxygen in the flue gas, on the same side, by about 0.3%.

Flame investigation experiments were performed for three different flame configurations: oxygen enriched flame, flame with portion of the fuel admixed to the all four air nozzles, and a flame with a portion of the fuel admixed to the two nozzles on the right side of the burner. The evolution of two important radical species, OH and CH, was observed and quantified at one-inch increment along the flame using the laboratory version of the Rich/Lean sensor.. Furthermore, emissions (O_2, CO, CO_2, and NO_x) from the flue gas were measured at the right and left side of the burner with a Horiba portable gas analyzer.

	Fuel Admixing Rate (L/min)				
	1	2	3	4	5
All nozzles admixing	✓	✓	✓	✓	✓
2 right nozzle admixing	✓	✓	✓		

Flame shown in Figure 13, with no fuel or oxygen injected into any of four air nozzles was selected as a reference flame (base flame). Figure 14 shows the OH and CH emissions profiles evolution for the base case (Air=162 l/min, fuel=15L/min). OH and CH intensities were measured 1, 3, 5 and 7 inches from the base of the flame. All emissions were quantified in arbitrary units (ABU). Exited specie emissions are more pronounced at the center (5 inch) than at either the base (1 inch), onset of ignition or the tip of the flame (7 inch).

Figure 13. Photograph of a reference (base) flame (Air=162, fuel=15 Liters/min). Note left and right nozzles and symmetric flamelets.

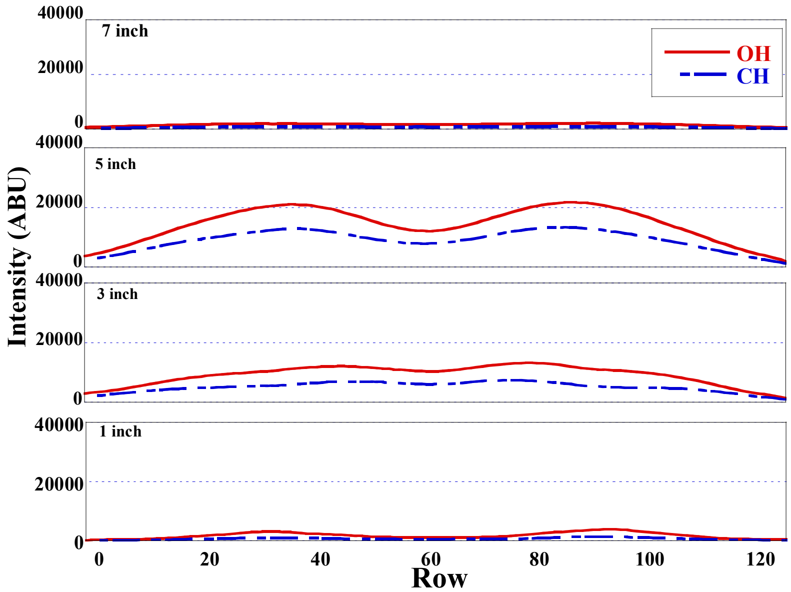


Figure 14. Species profile for a base case flame.

Oxygen was mixed with air such that the oxygen content in the oxidizer stream became: 25, 28, and 30%. Oxygen enrichment considerably increased luminosity of the flame as well as resulted in significant extension of the combustion reaction zone as portrayed in Figures 15 and 16. Oxygen-enriched flames are inherently sooty, emissions in visible and infrared regions of the flame emission spectra became more pronounced especially in the upper half of the flame.

Figure 15. Photograph of an oxygen-enriched flame for 30% oxygen

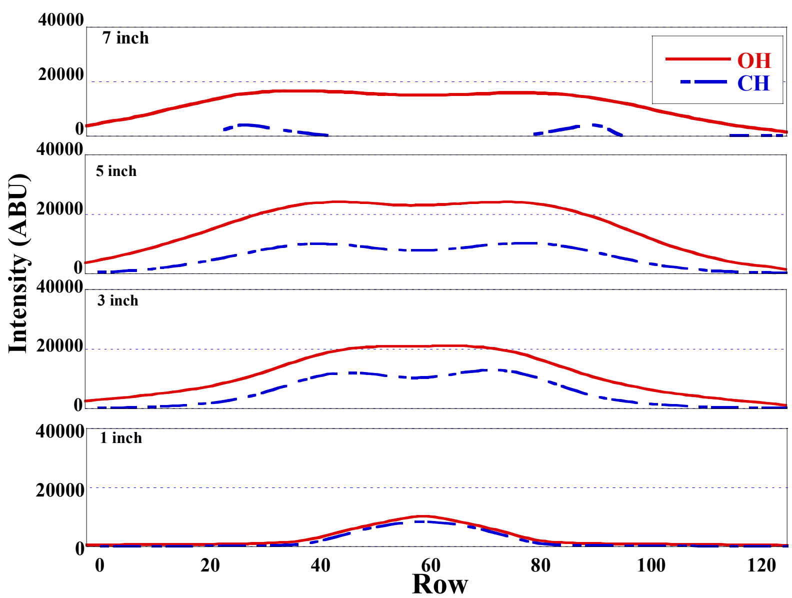


Figure 16. Evolution of an oxygen enriched flame. Oxygen content of the oxidizer is 30%.

For all flame configurations, exhaust gas was sampled at the right and left side of the burner for O_2, CO, CO_2, NO_x. Figure 17 reveals that the amount of leftover oxygen increases with addition of oxygen in the reactant stream. To enable comparison of flames with different oxygen concentrations in the oxidizer stream, the total flow rate of oxidizer and oxygen/fuel ratio were kept constant while varying the fuel rate

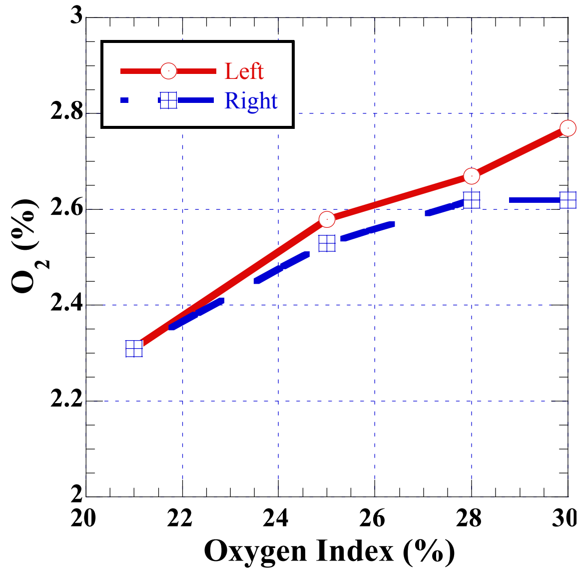


Figure 17. Emission of oxygen in the flue gas as a function of the oxygen content of the oxidizer for the left and right side of the burner.

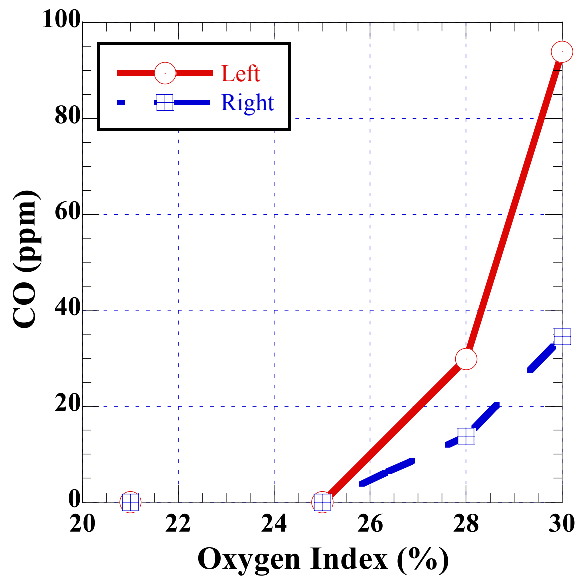


Figure 18. Carbon monoxide emissions

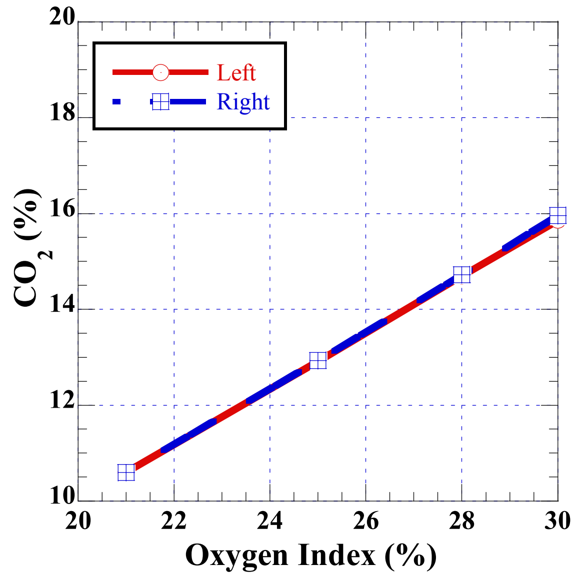


Figure 19. Carbon dioxide emissions

By flame chemistry, the production of CO is closely related to the flame temperature mainly determined by the oxygen concentration in the oxidizer. From Figure 18, CO is seen to not be produced from 21 to 25% oxygen, but CO rose exponentially at 28 and 30% oxygen.

In Figure 19, the production of CO_2 is shown to rise linearly with oxygen index. With the rise of shares of oxygen and fuel in reactant mixture, the level of CO_2 increases. The increase in NO_x productions shown in the Figure 20 is due to stronger Zeldovich 's NO_x production in higher temperature oxygen enriched flames. From a pure air flame to slightly enriched at

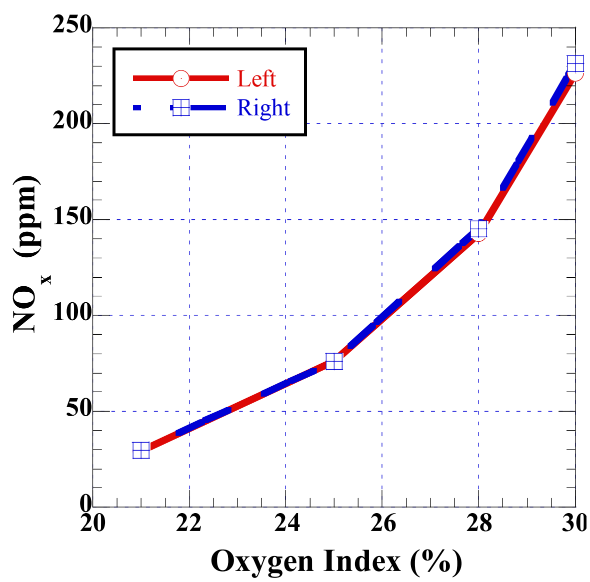


Figure 20. NO_x production as a function of oxygen index.

25%, the amount of NO_x almost triples from 29 to 76 ppm. It again doubles from 76 to 150 pmm at indices of 25 to 28% . The levels of NO_x reach close to 250 ppm by an index of 30%.

The next set of experiments focused on studying effects of admixing portion of the fuel inside the individual air jets. The total fuel flowrate of 15 L/min was kept constant by balancing the fuel supplied though the fuel nozzle. For example, when 3 liters of fuel were admixed to the air nozzles (0.75 liters per nozzle), the amount of fuel supplied though the central fuel nozzle was reduced to 12 liters per minute. Visually, only slight differences can be observed between an admixed flame and a non-admixed one at an admixed rate of less than 3 L/min. The captured OH and CH radicals' emissions showed minute variation between the two types of flames. Figure 21, a profile of an admixed flame, exhibits similar character to the non-admixed flame in Figure 14 such that species intensities are the same at all heights except at 3 inches where OH intensity surpasses the base flame intensity at comparable height in Figure 14. These facts suggest that oxidation combustion processes begin much lower, near the face of the burner, in the flame. Comparison of figures 2 and 9 shows that OH intensities are higher than the corresponding OH profiles in figure 2 (base flame), while CH emissions profiles appear to be near identical on both figures.

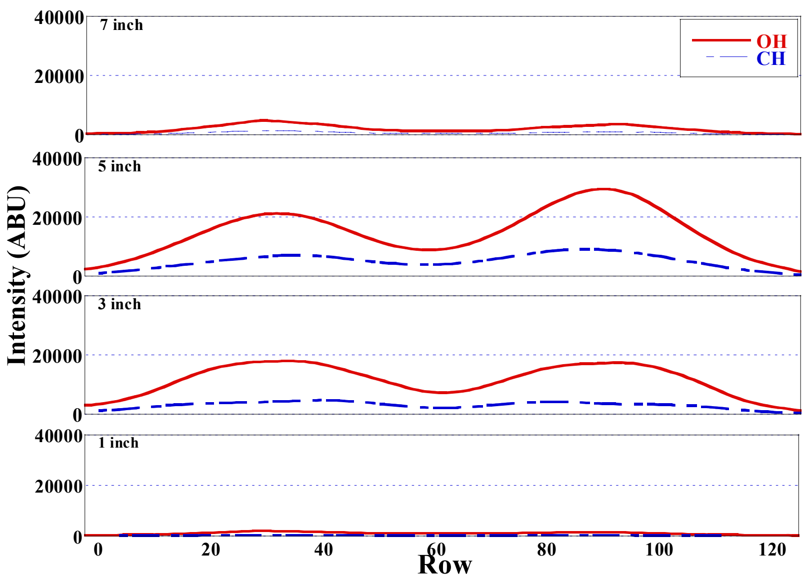


Figure 21. Flame profile at an admixing rate of 5 L/min.

NO_x values drop almost linearly along the tested domain, 0 to 5 liters in Figure 22. Values decrease from approximately 31 ppm with no admixing to less than 25 ppm at the maximum gas injection.

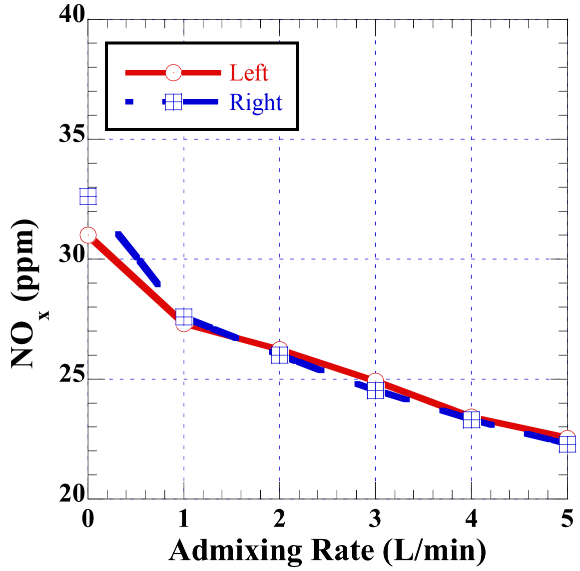


Figure 22. Oxides of Nitrogen.

In the next set of experiments, fuel was admixed to the two right nozzles while still maintaining the total fuel flow rate at a constant value.

Figure 23. Asymmetric flame produced by fuel admixing at a rate of 3 L/min to two right nozzles.

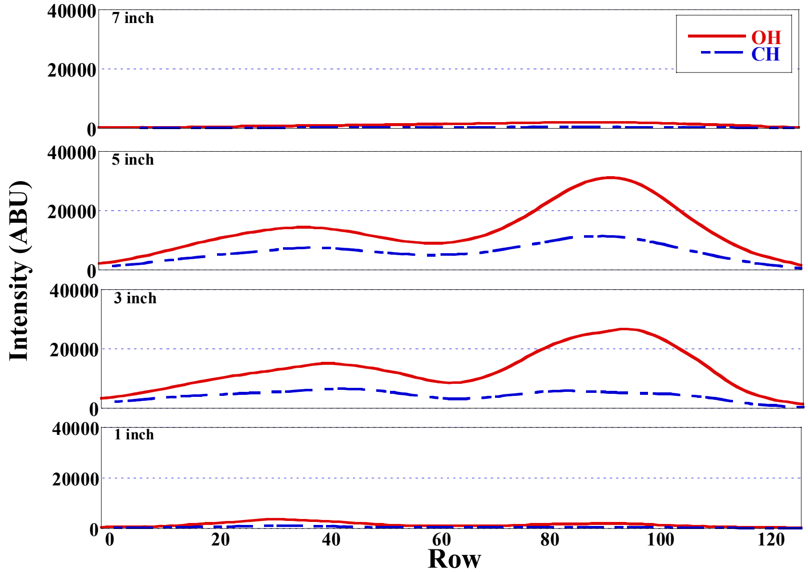


Figure 24. Profile for right nozzles admixing of 3 L/min.

The photograph in Figure 23 shows that the right side of the flame became more luminous than the left side from mid-flame onward. Spectral data in figure 24 also reveal that OH intensities are stronger in the right side of the flame relative to those measured in the left side

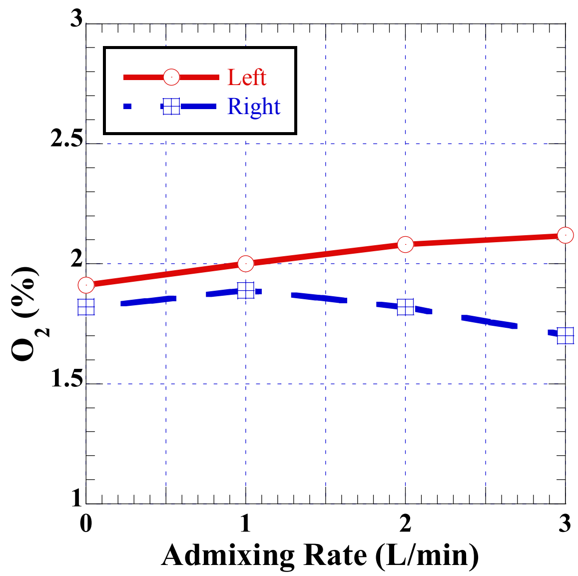


Figure 25. Oxygen as function of admixing rate for 2 right nozzle gas injection.

Figure 25 shows that the left side of the burner emits more oxygen than the right side.

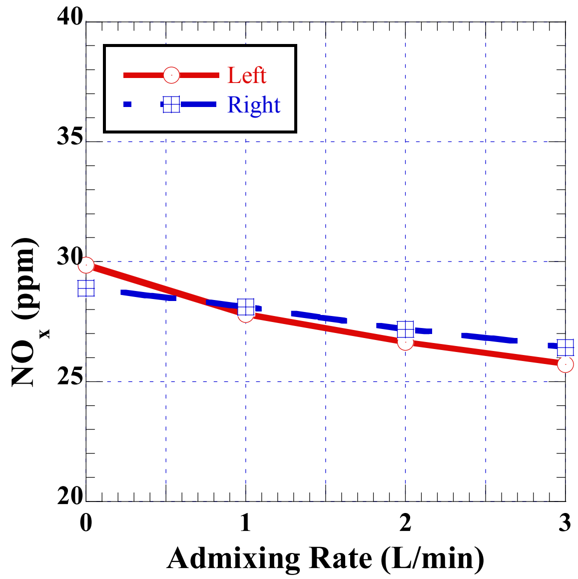


Figure 26. NO_x concentrations for the left and right side of the burners with fuel admixed to the right nozzles.

Four nozzle fuel admixing resulted in lower NO_x emissions relative to no admixing base case. The reduction is likely a result of an expansion of the reaction zone and consequential flame temperature reduction.

In the last quarter GTI completed the conceptual design of a nozzle mixed burner capable of firing at a rate of 0.5 MMBtu/hr. This burner's internal mechanism is able to create a hybrid flame with two distinct zones, where the excess air level in each zone can be independently controlled. More specifically, the lower portion of the hybrid flame will be fuel rich in order to inhibit dross formation, whereas the upper portion will be fuel lean in order to complete combustion and meet emission standards. In addition, the design of this burner will allow it to create a variably shaped flame, thus enabling the burner to be used in a variety of different furnace styles and geometries. The flame-shaping feature will permit this burner to deliver a heat load while maintaining temperature uniformity in the furnace and minimize hot spots.

PROBLEMS ENCOUNTERED

No significant problems were encountered during the second year of the project. One issue being addressed that could become a concern in certain industrial environments is the requirement of a clean signal to the sensor. Objects within the space above the melt, including furnace equipment and air-borne particles, could interfere with the signal to the sensor. The project team feels this concern can be addressed because the sensor only requires a periodically clear view of the flame and not a continuous clean signal.

A second concern is completion of the pilot-scale and demonstration-scale testing by 2003. The project team will be testing a pilot-scale burner this fall in the GTI laboratories and conducting a demonstration test in 2003.

MILESTONES AND FUTURE WORK

A milestone chart is attached at the end of this report showing all project milestones for three years. The milestones for this second year of the project are also shown. The milestones for Year 1 are described as –

- Design and fabricate pilot-scale flex-flame burner
- Integrate on pilot-scale furnace
- Complete pilot-scale testing
- Select host site for demonstration testing
- Modify the initial Industrial Adoption Plan

All of the milestones from the first year of the project have been met except for outlining the Industrial Adoption Plan. The milestones for year two are scheduled to be completed early in the third year of the project. The Industrial Adoption Plan will be developed in the third year after the burner and combustions system costs and the benefits achieved are determined. A project review meeting is expected to be held in October, 2002, and results of all second year efforts will be presented at that meeting.

Work will continue in Year three by following the project plan and milestones as shown below. Work will focus on combining the sensor and flex-flame burner into a complete combustion system. Testing will be conducted at GTI on a pilot-scale level and at Wabash Alloys on a working reverberatory furnace. Parametric testing will be conducted, and benefits of this new technology will be documented. The Industrial Adoption Plan will be prepared at the end of the project.

DOE F 4600.3
(03-94)
Replaces EIA-459B

OMB Control No.
1910-0400

U.S. DEPARTMENT OF ENERGY
FEDERAL ASSISTANCE MILESTONE PLAN

OMB Burden Disclosure Statement

1. Program/Project Identification No. DE-FC0700ID13903	2. Program/Project Title High-Efficiency Low Dross Combustion System for Aluminum Remelt Reverberatory Furnaces
3. Performer (Name, Address) Gas Technology Institute 1700 S. Mount Prospect Rd. Des Plaines, IL 60018	4. Program/Project Start Date June 15, 2000 5. Program/Project Completion Date June 14, 2003

6. Identification Number	7. Planning Category (Work Breakdown Structure Tasks)	8. Program/Project Duration A O D F A J A O D F A J A O D F A J	9. Comments (Notes, Name of Performer)
1	Des/fab lab-scale flex-flame burner		GTI/UIC
2	Select non-intrusive optical flame sensor		GTI
3	Complete lab-scale testing		GTI
4	Outline initial Industrial Adoption Plan		All
5	Des/fab pilot-scale flex-flame burner		GTI/Eclipse
6	Integrate on pilot-scale furnace		GTI/UIC
7	Complete pilot-scale testing		GTI
8	Select host site demonstration testing		All
9	Modify the Industrial Adoption Plan		All
10	Complete baseline furnace		All
11	Des/fab/install full combustion system		GTI/Eclipse
12	Complete demonstration-scale testing		GTI/Eclipse
13	Complete the Industrial Adoption Plan		All

10. Remarks

11. Signature of Recipient and Date	12. Signature of U.S. Department of Energy (DOE) Reviewing Representative and Date

DOE F 4600.3
(03-94)
Replaces EIA-459B

OMB Control No.
191-0400

if this form is used as a plan:

No grant or cooperative agreement may be awarded unless a completed application has been received (DOE Organizational Act, PL. 95-91; 42 USC 7254 and Federal Grant and Cooperative Agreement Act of 1977; PL.95-224; 41 USC 508)

If this form is used as a report:

No further monies or other benefits may be paid out under this program unless this report is completed and filed as required by existing law and regulations (DOE Organizational Act: PL. 95-91; 42 USC 7254 and Federal Grant and Cooperative Agreement Act of 1977; PL. 95-224; 41 USC 508)

FEDERAL ASSISTANCE MILESTONE PLAN

PURPOSE

The Milestone Plan is used as a planning tool, establishing the time schedule for accomplishing the planned work. Usually, it is accompanied by the DOE F 4600.A, "Milestone Log."

INSTRUCTIONS

Item 1 - Enter the Federal grant or agreement identification number for the current year as it appears in the official award, if known.

Item 2 - Enter the identifying name or description of the program/project, and, if applicable, the project identification number.

Item 3 - Enter the name and address of the performer responsible for managing the task.

Item 4 - Enter the original start date of the program/project.

Item 5 - Enter the official completion date as of the latest modification.

Item 6 - Enter the milestones' identification numbers from the work breakdown structure or as assigned by the U.S. Department of Energy (DOE) program office or managing office.

Item 7 - Enter a brief, identifying description of the milestones.

Item 8 - Enter the first letter of each month of the program/project duration in the appropriate boxes if the duration is 24 months or less. Divide the program/project time period up into intervals of two or more months for durations longer than 24 months and enter the first letter of the last month of each interval in the appropriate box.

Item 9 - Enter the name of the organization responsible for performing the work if different than in item 4 or any note for clarification of line entries.

Item 10- Enter any explanatory notes. If more space is required, attach additional sheets and so indicate in this block.

Item 11- Enter the signature of the Federal Assistance Recipient and the date signed to verify that the information is reasonable, based on knowledge of the project.

Item 12- Signature of the DOE reviewer and the date signed, which indicates that the information on the plan has been reviewed and appears reasonable.

CHARTING INFORMATION

SYMBOLS			EXAMPLES
∈	Major Milestones	A	Major milestones with an activity bar
		B	Time now and work done
↔	Intermediate Event (Deliverable, Supporting Milestone, or Decision Point)	C	Schedule Deviation (not yet approved)
>	Intermediate Event completed or late	D	First changed approved (slippage)
□	Proposed Scheduled Deviation (late or early) for a major milestone	E	Improvement, not contractually implemented
9	Activity Bar	F	First change approved (improvement)
____	Dollar Ceiling	G	Activity ahead of schedule
: l ---	Time Now		
(( )) ---	Continues beyond Time frame	H	Activity behind schedule

Late and on time completion of intermediate events A and B, respectively.

Same as Example 1 above except that here a time line is used in place of an activity bar.

Original major milestone date and four subsequent approved changes (all slip-pages) to that date

Original major milestone date and two subsequent approved changes (one slip-page, one improvement to that date)
Intermediate event schedule deviation